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CHAPTER 10

CABLE MANUFACTURING [10-1, -2]

Lawrence J. Kelly and Carl C. Landinger

1. INTRODUCTION

Insulated electric power cable manufacturing involves a broad range of complexity depending on the cable design to be produced. Different cable plants may be capable of a limited or broad range of designs. Then, those capable of a broad range may limit operations to only a few steps in the manufacturing process.

Despite this large variability in plants, the steps in the manufacture remain basically the same, whether done in one facility or a number of facilities. Conductor manufacturing, in Chapter 3, is common to all cables with metallic conductors. The manufacture of extruded dielectric power cables and laminar dielectric power cables follow.

2. CONDUCTOR MANUFACTURING

In Chapter 3, Conductors, it was pointed out that for efficient distribution of electric power, the conductors must be produced from a high-conductivity material. It was also shown that copper and aluminum offer the best available combinations of conductivity, workability, strength, and cost to become the most popular power cable conductor materials. From the conductor manufacturing standpoint (we will not attempt to include mining, refining, and fabricating stages), we will begin at the point where copper and aluminum are received as large coils of round rod. The diameter of aluminum rod for conductors is commonly 3/8 inch (0.375 inches). For larger solid conductors—i.e., 1/0 AWG or larger—it is common and necessary to begin with a larger-diameter rod.

2.1 Wire Drawing

In wire drawing, the copper or aluminum rod is drawn through a series of successively smaller dies to reduce the rod to a wire of the desired diameter. The quality of the wire surface depends on sufficient drawing and reduction to eliminate surface defects. Thus, there is the need to utilize a rod having a

diameter significantly larger than the solid wire to be produced. If fine wire is desired, it is common to utilize a coarse wire drawing machine followed by a fine wire drawing machine. The wires are taken up on spools for later stranding operations or on reels for use as a solid conductor.

2.2 Annealing

Drawing copper or aluminum wires increases the temper of the metal. That is, a rod of a “softer” temper is “hardened” as the wire is drawn down to the required diameter.

Except for the use of full hard temper aluminum stranded conductors for electric utility outside plant secondary and primary cables, it is generally desirable to use a softer temper.

To produce a softer temper, the wire is exposed to elevated temperatures well in excess of emergency operating temperatures of the cable. For many years, this has been accomplished in a large oven. Exposure time using this method is a matter of hours.

It is possible to partially anneal wires “on the fly”. This is generally done on a wire before it is used in a stranding operation. The method is not generally suitable for full annealing to a soft temper nor to conductors after they have been stranded.

3. EXTRUDED CABLE MANUFACTURING

3.1 Insulating and Jacketing Compounds

There are literally thousands of insulating and jacketing compounds used in the cable industry. Many of these compounds are commercially available from compound suppliers. They may also be custom compounded by companies that sell them as finished, “ready-to-extrude” compounds. The cost of “ready-to-extrude” compounds is high enough so there is considerable incentive for the manufacturer to mix many compounds in-house. Low voltage compounds provide special opportunities ranging from the simple addition of one or more ingredients at the extruder to the complete mixing of all the ingredients and production of strips or pellets suitable for extrusion. The complex subject of compounding is beyond the scope of this text. For our purposes, we will assume compounds are complete, “ready-to-extrude”. However, it is necessary to recognize that this all important compounding step is increasingly becoming a part of the manufacturing process.

3.2 Extrusion

The method of extrusion currently in use to produce polymeric layers comprising the cable are similar regardless of the polymer or layer being extruded.

Compound, in the form of pellets or strips, is fed into the back of a screw which rotates in a barrel. The material advances down the screw and is melted during the advance. In general, the barrel is divided into zones which are individually temperature controlled. There are some extrusions where the barrel is heated at the start of the extrusion, but as the extrusion continues, the mechanical shear and friction results in sufficient heat generation that barrel heating is no longer required. In fact, depending on compound and extrusion parameters, barrel cooling and even screw cooling may be required. Properly executed, the compound is all melted and forced through a die-head arrangement that deposits the melt on the core being passed through the head. This core may be a bare wire or cable in some stage of completion.

In many cases, the compound is introduced in its finished state. However, variations such as the addition of curing peroxides, color concentrates, or other ingredients at the extruder are quite commonly used.

3.3 Curing

This term is somewhat of a carryover from the rubber materials which required curing. The crosslinking process for modern thermosetting compounds, such as crosslinked polyethylene and ethylene propylene rubber, is often referred to as a curing stage. While materials such as polyethylene can be crosslinked by a radiation induced reaction, the majority of crosslinking continues to be by the chemical means.

Taking a simple case of polyethylene, the addition of a peroxide agent such as di-cumyl peroxide to the polyethylene and supplying heat energy results in a chemical reaction which crosslinks the polyethylene. Peroxides are also used for crosslinking EPR compounds.

The heating period to effect crosslinking is commonly called curing. It is also referred to as vulcanization, hence reference to the CV tube is the "continuous vulcanization" tube.

Curing tubes have three distinct configurations. The most commonly used is a curved tube that is in the shape of a catenary. The first portion is the curing section and the lower portion is the cooling section. The shape is designed to prevent touch-down of the cable until the cable has cured. The weight of the

cable, line speed, and length of the total tube must be considered in this design.

Other forms of curing tubes may be horizontal or vertical. Horizontal tubes are used for very small cables or in special extruders that employ very long dies. A vertical extruder has the advantage of being able to make very large cables, especially transmission cables. They run relatively slowly, but gravity does not work to deform the shape of the cable.

The heat source most commonly used in the past was steam in a tube through which the extruded cable was passed. This continues to be the most popular means for curing secondary cables. When curing relatively heavy walls such as primary cables, the upper limit on temperature that steam can practically impose makes it desirable to use other heat sources. The most popular heat source today in radiant heating in a nitrogen filled tube. This is one of a number of dry curing methods. This method allows for much higher curing temperatures and therefore faster line speeds and curing. These curing tubes are divided into a number of zones each of which has its individual temperature controls. This allows for optimum temperature profiling to effect cure.

Because of the high temperature involved, care must be taken to avoid thermal damage of the polymer. More common in Europe and gaining in popularity in North America for cables up to 600 volts is silane curing. The system is based on the technology of silicones and "sioplas" as originally developed is a two part system of crosslinkable graft polymer and a master batch catalyst.

A further development, "monosil" introduces ingredients at the extruder and thus eliminates the grafting process. Water is the crosslinking agent in these silane systems and cure rates become very thickness dependent.

3.4 Cooling

Thermoplastic materials, such as polyethylene or polyvinyl chloride, do not require curing. Single layers that are relatively thin -- such as 600 volt building wire -- may be cooled in a water trough following extrusion. In the case of polyethylene, care must be taken to avoid too rapid a quench. This rapid cooling can result in locked-in mechanical stresses which will result in shrink-back of the material on the wire.

Heavier thermoplastic layers, such as encountered on primary cables, require gradient cooling to avoid these stress in the polyethylene.

Following curing, thermosetting materials must also be cooled. Then steam is the curing medium, water cooling is universally employed. Crosslinked polyethylene must not be rapidly quenched to avoid "shrink back" that is caused

by locked-in stresses. Cooling zones are used to control the cooling process for water cooled cables.

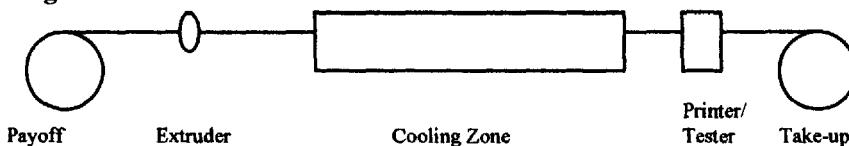
With the dry cure process, there is the possibility of using nitrogen as the cooling method. This is not frequently used for cables at this time. Cooling is sufficiently gradual that stresses are not locked-in.

4. EXTRUSION LINE CONFIGURATIONS

4.1 Straight Line

The simplest configuration for an extrusion line is one that can be used for low voltage thermoplastic cables having a single plastic layer over a conductor. A few examples of cables that are produced this way are: linewire, building wire, or a jacket over other cores.

Figure 10-1
Single Extrusion

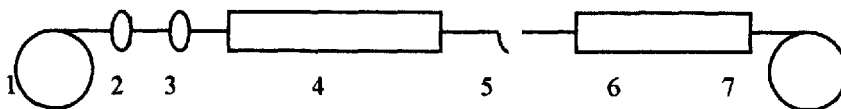


A curing zone may be added just before the cooling zone if curing is needed.

4.2 "Two Pass" Extrusion

Thermoplastic primary cables have been produced in a similar straight line configuration, but two separate extruders were used to apply the conductor shield and the insulation. Another "pass" through the third extruder after the first two layers were applied and cooled became known as "two pass". The figures that are shown here do not imply that the curing and cooling tubes are straight. The figures are representing all possible configurations.

Figure 10-2
Dual Extrusion



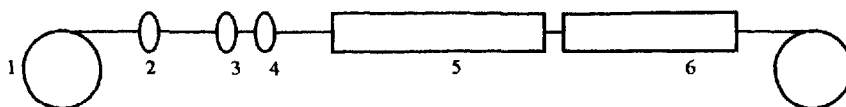
Where 1 is payoff, 2 is conductor shield extruder, 3 is insulation extruder, 4 is first cooling zone, 5 is insulation shield extruder, 6 is second cooling zone (for the insulation shield), and 7 is the takeup reel.

If the product was to be cured, a curing zone had to be included. Note that the third extruder, (#5 in Figure 10-2), was placed after the first cooling zone. That made it difficult to impossible to maintain the desired strippability of thermosetting insulation shields over thermosetting insulations. Thus, it was common to utilize a thermoplastic insulation shield over thermosetting insulation.

4.3 "Single Pass" Extrusion

The development of semiconducting thermosetting shield materials that would be readily strippable from thermosetting insulation even though all three layers were cured at the same time led to the development of lines where all three layers of a primary cable could be extruded over the core prior to any curing or cooling.

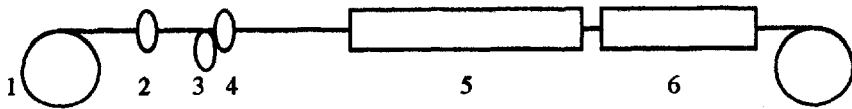
Figure 10-3
Single Pass with Three Extruders



Where 1 is the payoff reel, 2 is the conductor shield extruder, 3 is the insulation extruder, 4 is the insulation shield extruder, 5 is the curing zone, 6 is the cooling zone, and 7 is the take-up reel.

This was the first time the "triple extrusion" term was applied. While this arrangement was preferable to all previous methods because of minimal exposure of the insulation to possible contamination or abuse, further developments were desired. Dual extrusion of the two layers at positions 3 and 4 above would make for a smoother interface. Thus, the next improvement was single extrusion of the conductor shield and then, a few feet away, the dual extrusion of the insulation and the insulation shield. This was also called "triple extrusion"! About this time, dry curing lines were growing in popularity and many lines of this type were installed.

Figure 10-4
Single Pass with One Dual Extruder



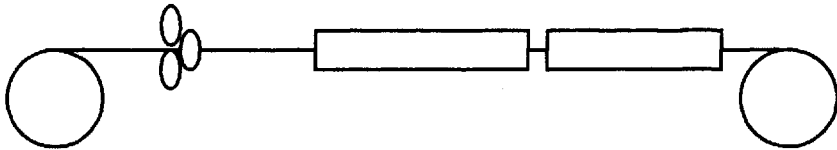
Where the equipment is the same as in Figure 10-3 except that extruders 3 and 4 are now in one “crosshead”.

Unfortunately this method continued to allow the conductor shield to be vulnerable to scraping in the next extrusion head, continued to allow build-up on the extruder die face (die drool), and exposed the conductor shield to the environment.

4.4 “True Triple” Extrusion

The method now used for the majority of medium voltage cables utilizes a single crosshead where all three layers are applied simultaneously. This is referred to as “true triple” extrusion.

Figure 10-5
True Triple Extrusion



All three extruders feed into a single head for “true triple” extrusion. There are numerous lines now in service in North America, and the world in general, that make use of these triple heads.

4.5 Assembly

In cases of covered overhead service cables and similar constructions, a number of single cables may be assembled as a group. This is done on cablers or twisters. The equipment has some similarity to the equipment discussed under stranding. For assemblies to later be jacketed and serve as multi-conductor cables, it is common to add fillers to “round out” the assembly as well as using

taping heads to apply binder and jacketing tapes in the same operation.

5. PAPER INSULATED CABLES

5.1 Paper Insulation

It has been found that up to a certain point, the mechanical strength of paper increases with its moisture content. Accordingly, prior to their use in the taping machine, pads (rolls) of paper are conditioned for a definite period in a room in which the temperature and humidity are controlled. This procedure assures that all the paper is in the same condition as it is being applied over the conductor and results in more uniformity in the taped insulation. When the paper is dried prior to impregnation, the paper shrinks uniformly. This allows for cables with sector conductors to be cabled without wrinkling.

5.2 Paper Taping

The importance of controlled tension in the taping process is realized when one is reminded that to have an optimum of electrical strength, paper insulation must be tightly applied, free from wrinkles, and other mechanical defects that non uniformly applied layers of tapes would have. Close, automatic control must be accomplished.

In one method, the tape from the pad passes around a pulley that is geared to a small motor armature whose direction or rotation is opposite to the direction of tape feed. As the tapes feeds along, the armature is revolved opposite to the direction it would take if turning freely and against the motor field torque. The pulley, therefore, exerts a back pull on the tape at all times and with a constant value. Torque must be regulated to the tension that is required.

5.3 Cabling

A large cabling machine is used for assembling individually insulated conductors into two, three, or four-conductor cables. The cradles may be operated rigidly or in a planetary motion to accommodate the large diameter cabling bobbins. This reduces the bending stresses to which the paper is subjected. Facilities are provided for mounting smaller bobbins between cradles which may be used for fillers, smaller cables such as fiber optic, or tubes. Small packages of fillers may also be carried on the spindles. Guides and bushings are used for placing sector-shaped conductors in their proper position without undue strain on the insulation. Behind the assembly bushings, heads are mounted for applying paper tapes on non-shielded type cables, or in the case of shielded cables, intercalated binder tapes.

Metal binder tapes are spot-welded when a new pad of tape is inserted in a taping head. The cable is drawn through the machine by a large capstan to a take-up reel. The large diameters of the capstan and impregnating reels reduce the bending stresses in the insulation.

5.4 Impregnating Compounds

Paper cables have been impregnated with numerous compounds over the years. A few of these that have been used include:

- Type A. Unblended naphthenic-base mineral oil.
- Type B. Naphthenic-base mineral oil blended with purified rosin.
- Type C. Naphthenic-base mineral oil blended with a high-molecular-weight polymer.
- Type D. Petrolatum blended with purified rosin.
- Type E. Polybutene

When paper-insulated cable is impregnated with a dielectric fluid, the combination is better than either part and results in valuable characteristics:

1. High initial electrical resistivity.
2. Low rate of deterioration from high temperatures.
3. Extremely low power factor.
4. Very flat power factor vs. temperature curve.
5. Low ionization factor.

Careful investigation has shown that the unblended mineral oil is the most stable oil from a chemical and electrical standpoint. Natural inhibitors in the petroleum afford high oxidation stability.

These inhibitors are complex resins occurring naturally in crude petroleum. For the most part, they are eliminated in the refining process and necessarily so because they represent impurities. If the petroleum is over-refined, all these inhibitors are removed, resulting in a clear oil of high electrical characteristics but having unstable qualities. These resins act as anti-oxidants by taking up oxygen themselves from the oil and thus inhibiting oxidation deterioration. In the refining process used for this oil, a good balance is obtained between electrical characteristics and high thermal stability. Most of the oil impregnated, medium voltage cables were made with Type A compound. Types B, C, and D were more viscous than Type A and were suitable for long vertical runs or slopes with Type C being the most frequently used compound.

The predominant compound used since 1980 has been the synthetic material polybutene. Since this is not an oil, it is proper to refer to these as fluid-filled

cables.

5.5 Drying and Impregnating

Assuming that the proper materials have been selected and good mechanical construction employed, the electrical characteristics of the completed cable depend primarily upon the drying and impregnating process.

It has been established by many laboratory investigations that oil, under heat and exposure to air, rapidly loses its desirable insulating properties. Also, the presence of residual air and moisture are harmful to impregnated paper insulation. Thus, paper insulated cables are dried and impregnated in a closed system.

The functional principles of this closed system are:

1. Transfer of hot impregnating fluid from a vacuum tank to another tank under vacuum without exposure to air.
2. Use of relatively high fluid pressure (85 to 200 pounds per square inch) during impregnation.
3. Complete degassing and dehydration of the fluid.
4. Use of extremely high vacuum (1 mm or less).

If there is more than one impregnating compound used in a plant, it is desirable to have separately assigned tanks for each material.

Prior to transfer to the impregnating tank, the fluid to be used is heated in its steam-jacketed storage tank where it is kept under vacuum. During this heating period, the fluid is agitated in order to maintain a uniform temperature.

In the center of each of the steam-jacketed vacuum and pressure impregnating tanks is a steam-jacketed cylinder of slightly smaller diameter than the hollow drum of the impregnating tanks. This reduces the amount of fluid subjected to heat during each impregnating cycle. Over the top of this cylinder, a large, circular baffle plate is mounted. When the fluid is admitted into the tank, it strikes this baffle where it forms a thin film. This affords an opportunity to subject the fluid to a second degassing treatment.

The impregnating of the paper can be considered to take place in two steps. First the fluid travels back and forth between the tapes from the outside of the insulation towards the conductor. This is best accomplished by applying

vacuum. Second, the fluid penetrates into the fibers of the individual paper tapes. This is accomplished by using pressure.

5.6 Conditioning the Impregnating Fluid

When the fluid is subjected repeatedly to the temperatures used in impregnating, it gradually loses many of its desirable properties. A plant to condition the fluid is frequently installed at the factory to ensure uniform quality fluid. Each of the vacuum operations is performed under a vacuum of one millimeter of absolute pressure. The proper temperatures for each operation are maintained by automatically controlled electric heaters. By the use of this equipment, the fluid is maintained at all times at a quality equal to that of the new fluid. This, together with the impregnating control, results in cables of uniform quality.

5.7 Control of Impregnation

In the manufacturing of solid-type paper insulated cables, the general practice is to regulate the drying and impregnating process by setting up standard periods of time for each operation. Slight modifications are made for the particular size and type of cable to be treated.

Due to the inherent variations in materials and manufacturing, dielectric measurements are made on the cable undergoing drying and impregnation. This control consists of periodic readings, giving an accurate measure of temperature and degree of impregnation. This established definite control throughout every step of the impregnating process.

Flexible electrical connections are made between the ends of the cable and the permanent terminals on the tank as the cable is placed in the tank.

The conductor resistance is converted to conductor temperature. Knowing the viscosity-temperature characteristics of the fluid, these combined data effect a control of the impregnating ability of the fluid. Dryness is determined by the constancy of the ac capacitance values. Thorough saturation is determined by the change in ac capacitance. Complete cooling is determined from the conductor temperature measurements.

5.8 Control of the Cooling Cycle

Uniform cooling at a defined rate produces high quality paper insulated cable. To accomplish this, a large refrigeration plant can be installed as part of the impregnating system. This enables the mill to cool the impregnated cables at a prescribed rate independent of the water supply temperature.

The cooling is brought into use after the impregnation cycle is completed. The temperature of the entire tank is reduced under this controlled cycle to room temperature. This is a gradual reduction that is made while the cable is still in the sealed tank. The seal is then broken and the cables, coated with a thick layer of fluid, are transferred to the lead press, or other sheathing process.

The lead presses that were used for most medium voltage cables in the past, could extrude lead under pressures of 3,000 tons. A lead charge of up to 2,000 pounds was placed in a melting kettle located adjacent to each press. The advantage of a large charge was that fewer stops had to be made. This stop could last for several minutes and for all of that time the cable in the die-block was subjected to high temperatures. Continuous extrusion techniques were also developed.

The melting kettle had automatic temperature control to keep the lead at the proper, molten state. An agitator was used to keep the metal stirred so there was no separation in the mix. Means were provided to removing dross (oxidized lead) from the top of the molten mass. Over the lead, an atmosphere of an inert gas, such as carbon dioxide or nitrogen, could be used to reduce the formation of oxides.

The lead sheathing process takes the impregnated cables through a steel die-block attached to the cylinder of the press. The die-block has a core tube having a diameter just large enough to receive the cable core and a die having an outer diameter of the sheath diameter. Pressure is exerted on the lead in its plastic state by a hydraulic ram or piston. The lead is extruded at temperatures of about 375 to 400 °F from the cylinder into the die-block and around the outer portion of the core tube. The lead is squeezed down over the cable to form a thick, continuous, homogeneous sheath. Pressure behind the lead tube forces the cable through the die-block.

When the cylinder is charged, it is overflowed and the exposed lead is allowed to congeal. The exposed lead is then skimmed off level with the cylinder by means of a mechanical guillotine or cropping device that removes all traces of oxide. The hydraulic ram, having a rounded nose, is then immediately brought down onto the surface of the skimmed surface of the lead.

The press is started and a quantity of lead pipe is extruded and checked to make sure the crystalline structure, welds, and ductility are satisfactory. After the cable is started through the press, a sample of lead sheathed cable is cut off and concentricity checked. As the cable leaves the die-block, it is water cooled and either given a jacket or a coating of grease, as required.

The discontinuous type of extrusion presses with vertical rams and containers

that had to be filled with liquid lead were largely replaced by continuous extrusion machines. The screw of these machines is vertical and lead is fed from the bottom end from a reservoir of lead. The extrusion temperature is about 300°C.

6. FACTORY TESTING

6.1 Electrical Tests for 100% Inspection

The Insulated Cable Engineers Association (ICEA) recognizes three alternative test methods for electrical testing of secondary cables (up to 1,000 volts phase-to-phase).

6.1.1 ac Spark Test. The cable conductor is grounded. The covered / insulated cable surface is passed through a close network of metallic bead chains or similar contact electrode. The electrodes are at an ac voltage potential selected on the basis of the type and thickness of the covering. In the event of a pinhole, skip, or other sufficiently weak spot (electrically speaking), a fault to the grounded conductor occurs. The fault triggers an alarm such that the operator can mark the fault for removal or repair.

6.1.2 dc Spark Test. This is similar to the ac spark test except direct current, higher potential values, and continuous circular electrodes are used.

6.1.3. Alternating Current Water Tank Test. The entire reel of finished cable is immersed in a water tank with only the cable ends protruding above the water. After a soak period to insure that water has permeated the entire reel of cable, the cable conductors are energized at an ac voltage level that is dependent on material type and thickness. The test voltage is applied for five minutes. The water acts as a ground and during the soak period it is hoped that water infiltrates in to any damage, pinhole, or electrically weak areas.

6.1.4. Insulation Resistance Test. For most modern insulations, this test is meaningless, but persists in industry standards. In connection with the water tank test above and while still immersed, a bridge is used to read the insulation resistance. For modern insulations, the readings are so high that "apparent" differences, even though possibly huge, are meaningless and dependent on numerous factors unrelated to the insulation resistance.

6.2 Testing Medium Voltage Cables.

The tests described under Section 6.1 are also applicable to medium voltage cables. These tests are generally conducted in a dry environment on finished cables.

Unique to medium and higher voltage cables is the partial discharge test. AEIC requires that such cables be subjected to a partial discharge while on the shipping reel.

The cable must be allowed to “rest” after manufacturing to allow any pressures that were developed during manufacturing to escape. It must be performed prior to the ac voltage test. Alternating current voltage is raised to an established level that is approximately four times operating voltage. The voltage is lowered while the partial discharge level in picocolombs is recorded.

Corona testing is extremely sensitive to defects in the cable as well as external electrical interference. Shielded rooms are provided to minimize this external noise.

7. REFERENCES

[10-1] Carl Landinger, Adapted from class notes for “Power Cable Engineering Clinic,” University of Wisconsin -- Madison, 1997.

[10-2] L. J. Kelly, Adapted from class notes for “Power Cable Engineering Clinic,” University of Wisconsin -- Madison, 1995.